

# Principles, Techniques and Approach Used in Conducting Program in Space System Engineering

## NASA-Stanford University Training Program

### Administrative Report

Prepared under  
National Aeronautics and Space Administration  
Contract NSR 05-020-151

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PRINCIPLES, TECHNIQUES AND APPROACH USED IN CONDUCTING  
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School of Engineering  
Stanford University  
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## ABSTRACT

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This report covers a summary of the principles, techniques, and approaches used in teaching a course in space system engineering. Most of it was prepared by the fifteen professors who participated in the NASA-Stanford Training Program during the summer of 1966. This summary was edited by the Stanford staff. During a period of 10 weeks the professor-trainees carried out a system engineering study of ICARUS, an advanced solar probe to explore the region of the solar system between 0.1 AU and 1 AU.

During the 10-week summer study the participants encountered similar problems and difficulties as well as successful achievements as are normally met by the graduate students over a 15- to 20-week course during the school year. Thus they obtained a good appreciation of what is involved in offering similar programs at their home schools.

Since the programs offered over the past four years at MIT and at Stanford have differed in some of the details, the procedures described in this report represent an average situation. Each school will undoubtedly vary its method of operation in some respects.

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## I. INTRODUCTION

### A. HISTORICAL BACKGROUND

Some experimental project courses have been conducted during the past four years at MIT and Stanford University in the design of relatively complex engineering systems. These projects utilized teams of graduate students from many disciplines of engineering supervised by faculty advisors and assisted by outstanding lecturers from industry and government.

Participation in these system-engineering projects has proved to be highly rewarding for both faculty and students. These projects turned out to be excellent ways for finding unsolved problems on the frontiers of technology; they provided opportunities for the graduate students to find useful engineering research topics and to exercise ingenuity in the design of clever solutions for these unsolved problems.

The following approach has been used at MIT and at Stanford during the past four years. Three to five professors from such fields as astronautics, instrumentation engineering, mechanical engineering, electrical engineering, and industrial engineering served as faculty advisors to the class. One of the professors was overall organizer and coordinator of the project. The advisors selected a class project which met the specifications that it represent a complex engineering system not yet designed nor in existence but which gives promise that it could be designed with the current technology and which would satisfy an important need of society.

The size of the classes has varied from 30 to 60 students. Most of them have been graduate students from engineering and science. In addition, a few students from such departments as English and Philosophy have participated on the editorial, planning, and evaluation functions. The course duration has been one semester at MIT and two quarters at Stanford.

About half of the lectures, dealing with fundamental principles, were given by the academic staff of the university; the other half, dealing with the state-of-the-art of the technology, were presented by engineers from industry and government. The students devoted 12 hours per week to this project (two afternoons of three hours each in class and six hours per week to direct project work). They organized the work under student

group leaders of their own choosing and changed group leaders every four weeks to provide the opportunity for project management to a large percentage of the students. One student served as project manager for each four-week period.

At the conclusion of the study, the students presented a three-hour briefing of their conclusions to leaders from industry and government, including the lecturers who had initially contributed to the course. In addition, they published a report of about 300 pages summarizing the conclusions and recommendations of their studies.

## B. COURSE OBJECTIVES

The purpose of a systems engineering course is to give students experience in and an appreciation of the overall problems in carrying out the preliminary design of a typical complex engineering system, while at the same time permitting them to examine in detail at least some novel aspects of that system.

Many engineering students in today's universities are not aware of the problems involved in pursuing an idea from conception to realistic design. They appreciate little of the interdisciplinary aspects of a design study. A system engineering course, patterned after the MIT - Stanford projects, helps to remedy the situation by placing the participant in a real life engineering environment. Some of the benefits of this approach, many of which are difficult to incorporate into normal engineering courses, are as follows:

1. A student's understanding of the engineering profession is broadened by his participation in the design of an overall system.
2. An opportunity for creative engineering is presented.
3. A participant develops more enthusiasm for engineering.
4. A student is exposed to the social, economic, and political aspects of engineering.
5. A student participates in the preparation of a report which is published and presented orally.
6. The course offers real opportunity for using and integrating material learned in earlier courses.
7. A participant discovers how little is known at some of the frontiers of technology. He thus recognizes that he can still make some important contributions to engineering.

8. A participant learns the importance of fundamental principles through their application to complex design problems.
9. The need for and difficulty of problem definition and modeling arises. The participant is forced to question many authorities to obtain answers both in person and through the literature.
10. The idea of team participation and the systems concept are introduced.
11. Communications between members of the various disciplines widens the horizons of the students.
12. Opportunities arise for finding promising research topics and for developing new design concepts and inventions.

The list is not complete but serves as a guide to goals which should be set for the course. Realistically no one course is likely to achieve all the goals set forth above; however, success in only a few of them will justify the course.

#### C. RELATIONSHIP TO ACADEMIC CURRICULUM

It has been suggested that a systems engineering course is best suited for seniors and graduate students, in order to make use of their previous formal classroom training in basic engineering fundamentals. Thus it might be advantageous if this course were used in place of the typical "Senior Project." Another alternative is to use the course in the fifth year of study in place of the master's thesis. Of course, the time allotment, credits, and relation to the overall curriculum must be tailored to each school's requirements and policy. To date, at both MIT and Stanford, the course has been offered at the graduate level for three hours of credit with six hours of scheduled class meeting per week. Stanford uses two quarters - MIT one semester.

It is generally agreed that, particularly in a graduate program, it is important to include students from many disciplines and with varied backgrounds. Students from Mathematics, Physics, Engineering, Business, and Social Sciences should find a system engineering program of great importance in their overall University training.

For example, in the 1965-66 Stanford Project, SPINMAP (an international weather forecasting satellite system), a graduate Law student contributed very useful information on the international legal problems. Participants

from food technology and the business school studied the economic value of improved weather forecasting, and students from industrial engineering evaluated the cost/benefit ratios of improved weather forecasting systems.

One key to a program of this type is the participation of faculty members who are imaginative and greatly interested in new developments and who have student meetings, field trips, and informal discussions. A committee, appointed by the Dean or Vice-President, of key members of all departments that would be involved in the course, would be of great assistance in the original planning and organization of the course.

## II. PRE-COURSE PREPARATIONS

### A. CHOOSING A PROJECT

In order to make the course experience as realistic as possible for the participants, the engineering project which is undertaken should be technically feasible and operationally desirable, but not yet designed or built by industry. The feasibility requirement would ordinarily require that some preliminary studies be carried out by the faculty leaders to assure that there is at least one possible solution to the problem. Besides this general constraint there are several other factors to be considered.

The project should be commensurate with the academic level and the interests of the students. To date, the MIT and Stanford course have been offered primarily on the graduate level. Undergraduates will probably do as well in most phases of the work but may lack the analytic tools or specialized knowledge to go into some of the finer details of the design. Obviously, a suitable project will provide opportunities for innovation and analysis by all students of all disciplines expected to enroll in the course. Other things being equal, a project which is more "glamorous" will generate more initial student interest.

Care must be taken to limit the extent of the project to that which might reasonably be handled by the available student man-hours. Experience has shown that time requirements for problem definition and conceptual design at the beginning of the course, and final report writing at the end of the course tend to be underestimated. The result is that over-ambitious projects get in a time bind in the numerical analysis and report writing phases.

Since a large part of the input to the students comes from lectures and informal discussions with faculty advisors and guest speakers, it is essential that the chosen topics be compatible with available expertise. Thus the research and teaching interests of the faculty advisor and to a lesser extent other campus personnel should be considered. Nearby industries, research labs, and educational institutions are the best sources of guest speakers. However, if the chosen project is too similar to studies under way by "for profit" organizations it will probably be

difficult to get outside speakers to give the students current information because this might violate company security. For this reason projects one step ahead of active commercial considerations are usually better.

To date four of the MIT and four of the Stanford projects have involved the preliminary design of space systems. In addition, MIT has undertaken two projects on earth-bound transportation systems. Besides space and transportation, some potentially valuable areas which have been considered are deep sea systems (harvesting systems), water resources, environmental control (smog control), educational technology (teaching machines, etc.), foreign development (agricultural or industrial development of underdeveloped countries).

It is expected that the choice of a project would usually be made by the teaching staff of the course.

1. Preliminary Assembly of Source Material

Because of the limited student time available and their initial lack of familiarity with the problem, one of the primary tasks in preparing for the course is the collection of essential source material. If possible this material should be available on a book shelf in the meeting room. It is expected, of course, that the students will find additional information necessary and will obtain it as the course proceeds.

2. Field Trips

It is traditional at MIT and Stanford for the class to visit Cape Kennedy or Vandenberg Air Force Base during the course as well as some nearby space related industries (if the project is a space system). Although such field trips may not be considered necessary, depending on the nature of the project itself and available source material, they stimulate student interest and provide an incentive-boost to the project as a whole. The trips are usually not arranged until after the course is in progress and the students' interest and information requirements are more clearly defined.

## B. ADMINISTRATIVE ARRANGEMENTS

### 1. Personnel Requirements

In the past there have been three to five "faculty advisors" associated with the class. One of these is designated as the Course Director. This job requires approximately one-half time during the term(s) the course is taught and at least a few hours per week during the preparation period. The Faculty Advisors should be available for two afternoons per week during the term of the course, and should participate in the planning sessions prior to the start of the course.

The equivalent of one full time secretary is required during the term of the course. During the initial half of the course, a competent secretary can relieve the project director of many of the details in arranging for visiting lecturers, visual aids, letters confirming invitation of lecturers, hotel and travel arrangements, expense accounts, thank-you letters, visit and tour clearances. During the second half of the course, the typing and reproduction of reports by student teams becomes a major task, and during the last two weeks of the course, it is desirable for one to three additional secretaries from other departments to assist in the typing of the final report.

Guest speakers should be contacted by phone well ahead of time, followed by a letter confirming their speaking date. Usually speakers from nearby industrial concerns and government labs which are interested in the topic under study are available at no cost to the university.

Speakers from other universities or nonprofit organizations and independent consultants usually receive an honorarium (\$100) and travel expenses.

### 2. Physical Facilities

It is desirable that a lecture room be available equipped with the usual visual aids (overhead projector, slide projector, motion picture sound projector, and tape recorder). The overhead projector is a most essential device to permit the student teams to prepare their own briefing charts, sketches, diagrams, etc. using grease pencil or equivalent

on a transparent 8-1/2 x 11 sheet.<sup>†</sup> Transparencies from printed material can be readily prepared by first making a Xerox copy on 8-1/2 x 11 paper from a book or magazine and then preparing a transparency with the aid of a Thermofax machine, using the appropriate type 3M brand projection transparency.

It is desirable that the lecture room also have space for the storage of reference books and for the posting of written data such as the most up-to-date specifications of the spacecraft weights, dimensions, etc. As an alternate the reference books may be kept on a special shelf in the engineering library.

Some means of reproducing various written material (magazine articles, charts, etc.) as the course proceeds is also usually required. The Ditto process is probably the least expensive but Xerox-type duplication is occasionally the only suitable means. The availability of these machines should be ascertained before the course begins. The students will probably have occasion to use drafting equipment and a digital computer. Provision for their use should also be made ahead of time.

A very desirable but unfortunately difficult arrangement is to secure a meeting room for the use of the systems engineering course exclusively. This would allow the students to set up helpful visual aids, diagrams on black boards, etc. and leave them undisturbed until the next meeting.

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<sup>†</sup> Reprocessed X-ray film makes an excellent low cost transparency for overhead projectors. In quantities of 1000 sheets this may be obtained at a cost of \$30 for 10 inch by 12 inch size (plus shipping charge) from Johnson Process Company, 88 Front Street, Elizabeth, New Jersey.

### III. COURSE ADMINISTRATION

#### A. CLASS ORGANIZATION

A systems engineering class is comprised of groups, group leaders, a project manager, and faculty advisors. During the planning phase in the organization of the course the topic of study is broken down into four or five major areas. Each of these will be studied by a group of students. The students are invited to select one of these groups as their first choice and another as their second choice. The faculty advisors then allocate the students in the class to these various groups, with due attention to obtaining a proper balance of skills in each group and to the desires of the students. Each group has a faculty advisor whose technical specialty should match the primary interest of the group. He is to be available to the group for consultation, and while not directing the group, the faculty advisor should maintain loose guidelines within which the group operates. Each group should consist of a proper balance of mechanical, electrical, aeronautical and other engineers appropriate to the task of the group, and not only electrical engineers or only aeronautical engineers, etc. It has been found best to have between three and six groups in the class. If there are less than three, the student is not exposed to the trade-offs that occur between groups. If there are more than six, a single project manager cannot coordinate the work properly.

The group leaders are elected by each group, and are responsible for guiding the work of their respective groups. The group leader conducts group meetings, assigns tasks within the group, and represents it in the meetings with the project manager. Weekly meetings of group leaders together with the project manager are held to coordinate the overall effort and to make major decisions.

One member of the class is selected as project manager, who is responsible for the entire project. It is his duty to conduct the group meetings, to be aware of the current status of the entire project, to assign tasks to the groups, and to represent the class in talks with the faculty and industry. He also works closely with the Course Director in maintaining the smooth operation of the course.

The project manager and group leaders have the responsibility for the management of the project. In their meetings, interaction problems are discussed, decisions are made, and the conclusions, with justifications, are presented to the class at its next meeting. An important part of this course is the opportunity for the students to participate in project management. Consequently, new group leaders and project manager are selected at about four week intervals. The project manager is elected first by a written ballot from a slate nominated by the entire class. The group leader is elected by a written ballot by the members of his group. No student is eligible to serve for more than one term as group leader or project manager. Usually the first election is called at the end of the second week of the course when the students have had a little chance to become acquainted with each other.

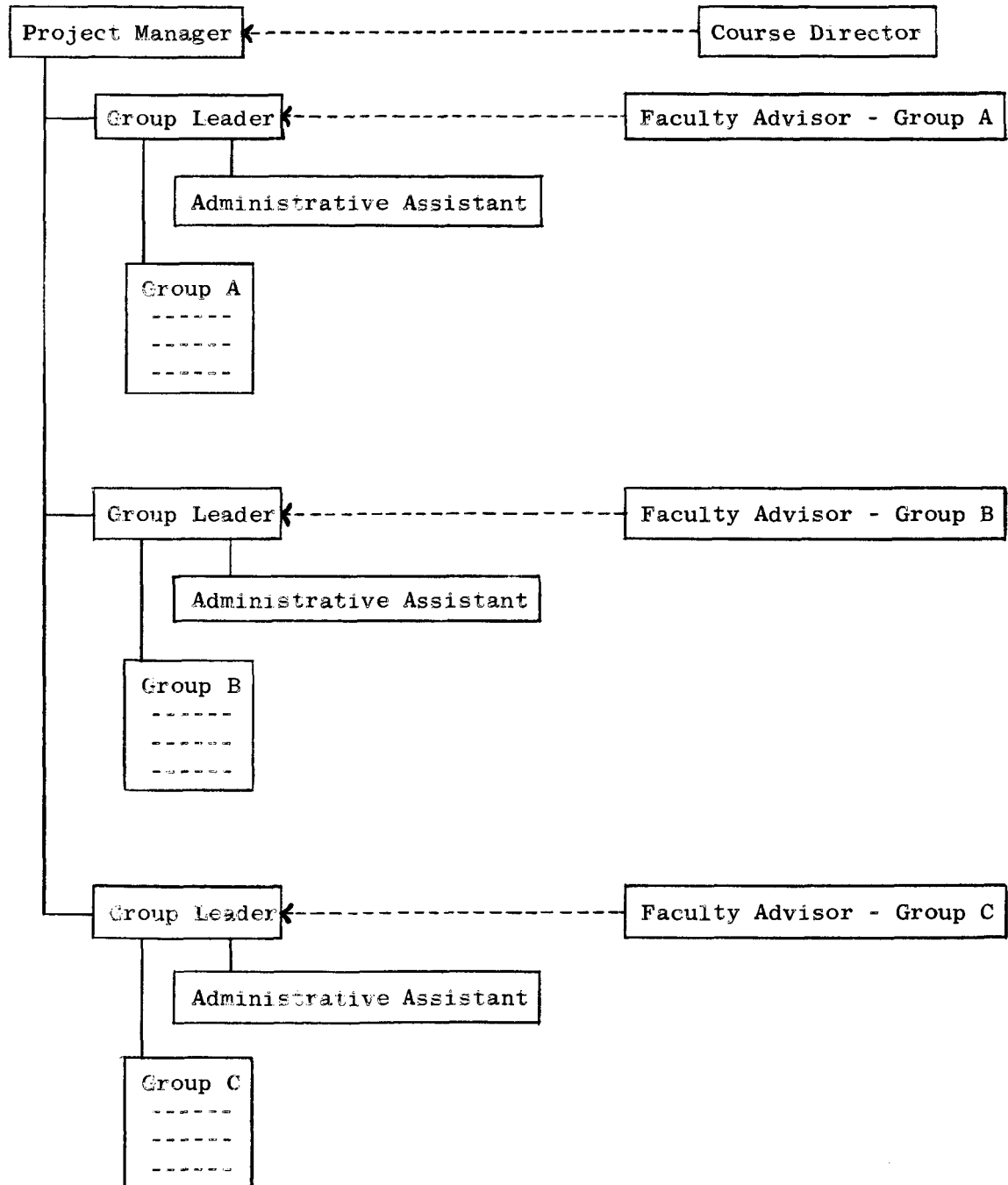
It is very desirable to include in the class students of Industrial Engineering or Business Administration with an interest in the functions of planning, scheduling, cost analysis and editing. These students can perform these supporting functions best by serving as administrative assistants to the group leaders. These administrative assistants to the group leaders provide continuity in the operation of the project. They will have coordinating meetings among themselves in order to assure that uniform procedures are used for scheduling, cost estimating, and for planning the final report.

It is important to emphasize, however, that the management of the project rests with the student elected project manager and the student elected group leaders. The function of the faculty director and advisors is to advise and recommend for consideration. Similarly, the function of the administrative assistants is to provide important administrative supporting services involving cost and time schedules. Some difficulty will be experienced if either the faculty attempts to dictate the decisions of the class or if the administrative assistants attempt to become the management group.

## Students

## Students

### Faculty Advisors



## B. GROUND RULES

Generally, the ground rules evolve only through a process of trial and error, and depend strongly on the individual personalities of the people involved. However, it does seem appropriate to mention a few rules which have proved useful in the past.

One of the main difficulties in a course of this type seems to be the lack of student ideas which are freely volunteered. The important rule to emphasize to the students, at the beginning of the course, is that particularly during the early brainstorming sessions new ideas including wild and unconventional approaches need to be considered. Ideas which at first may seem unworkable, can often be built upon to the extent that they can eventually be made practically feasible. Ridicule of new ideas will inhibit and discourage the presentation of unconventional solutions.

The advisor, of course, should not dictate decisions, but merely act as a technical advisor. He should, naturally, point out any serious errors and mention possible alternatives. However, as an advisor, he should avoid pointing out errors and making suggestions too early in the game lest the student be deprived of the valuable experience of discovering his own errors and thinking through alternative approaches.

The importance of a proper chain of command from the individual, to the group leader, and then to the project manager, must be emphasized. In this manner, students will get a true feel for the industrial chain of command. Since the jobs of group leader and project manager rotate, many students obtain experience at both ends of the ladder.

## C. INTRA-CLASS COMMUNICATION

A systems engineering course requires a student to work at times individually and at other times with a group. In either case, effective channels of communication are an essential factor to the coordination of the project as a whole. In past experience, it has been found that both written and oral methods of intraclass communication play important roles, depending upon the formality of the situation.

Written material includes prepared material which is made available to the class, such as "milestone" reports made up by the entire class as to the status of the project at pre-selected dates (preliminary design, midcourse design, final design). Other forms of this would be "current status" reports, recent drawings of the design, and prepared briefs given to the class by a group or individual. The prepared brief involves visual aids which demonstrate the major results obtained.

Perhaps the most important form of oral communication is the informal discussion in meetings of project management and in meetings of the groups. In full class meetings, short oral briefs may be presented on particular topics of interest by the person most concerned with the problem. Finally, the entire class should be available for consultation and discussion at specific times during the program so as to ensure a clear understanding by all members of the class as to what exactly each member has been doing.

#### D. THE DECISION PROCESS

The process of selecting alternatives as a design evolves can be among the most challenging and interesting aspects of an inter-disciplinary systems design course. If properly conducted, student interaction (the give and take as technical and cost trade-offs occur) will focus attention on the need for broad points of view to optimize or even achieve the design objective.

It will generally be found that a design philosophy will help direct the group's effort toward a productive end. Such considerations as economic feasibility, high reliability, state-of-the-art components to avoid development cost, light weight, etc., may dictate design philosophy. It may well be that the philosophical basis will need to be changed at some stage because of some newly uncovered concept or principle. Such changes are usually beneficial in the long run if adequately justified on the basis of some pay-off function.

It is obvious that crucial decisions will be made throughout the entire design procedure, sometimes directly and other times through default. In any case, economic and political, as well as technical matters, must be

given early attention. Costs and pay-offs should be defined as clearly as possible (usually these can be more exactly defined than is readily admitted). Parametric studies are encouraged, and certain hard decisions may call for a list of pros and cons under each of two or more alternatives. It is wise to avoid making any major decisions too early in the course; some free-wheeling ought to be allowed for generation of creative ideas at the outset. On the other hand, as the design is being finalized cost considerations may make it necessary to eliminate some aspects of the original design objective. In such cases the work of the students can still be included in the final report including the considerations why a particular experiment could not be included in the final system.

The process of making major decisions generally calls for all groups to be represented for effective interaction. All too frequently the process loses efficiency if vital information is missing which could have been readily supplied. It is well to start with an agenda and set a target time for the discussion of each item. Each session should be concluded with a plan of action and a clear understanding of the decisions which have and have not been made. Whenever a newly discovered factor dictates review of present methods, the alteration or substitution of past decisions should be handled in the same manner outlined above so as to avoid any confusion or contradiction.

One key to a successful decision procedure is the discussion leader. While tact is always appropriate he must create a situation which allows for free exchange of information, generation of creative ideas, and the liberty of freely challenging a premise. To focus attention he must be able to ask crucial questions, or get others to ask such questions, and be generally aggressive in moving the group toward its objective. An important part of such leadership is the ability to get each group to understand and perform its appropriate role throughout the design.

In order to prepare for the process of decision making it is recommended that each student prepare an evaluation on his part of the system. For example, for a satellite power supply:

1. A statement on the major alternatives available (solar cells, radioisotope thermoelectric generator, solar concentrator and thermoelectric batteries, etc.).
2. A summary of the factors for and against each of these alternatives, including a quantitative comparison wherever feasible (weights, costs, level of radioactivity, reliability, life time, state-of-the-art, etc.).
3. The implications on other parts of the system of selecting these alternatives (effect upon electronic elements of nuclear radiations, political obstacles in launching radioactive generators, etc.).
4. His recommendations.

This approach will permit each protagonist to present his ideas as clearly and as forcefully as he desires and to include these considerations in the final report even though the final decision may have been to reject a particular component or experiment.

#### E. SCHEDULING AND STAGES

The schedule for a systems engineering course involves overlapping periods of information gathering, preliminary design, trade-offs, and final design. Despite this overlapping, the course outline should include specific dates when significant portions of the design are to be completed.

A typical schedule is shown below:

- Weeks 1 & 2: Familiarization with problem and techniques involved. Students prepare three to six page conceptual designs in groups of two to three.
- Weeks 3 & 4: Organization of class into project groups; selection of group leaders and project manager; systematic study of various alternatives for each subsystem.
- Weeks 5 & 6: Decision on the most promising alternatives in more detail (each student submits a preliminary report summarizing the alternatives he has studied, the comparative performance, the pros and cons, and his recommendations for his component(s) of the subsystem); first trade-off sessions; selection by project management group of technical specifications for system.
- Week 7: Written preliminary design report.

Weeks 8, 9, 10, & 11: Selection of new group leaders and project manager; selection of editorial staff. Further design of subsystems; trade-off sessions. Written design report submitted.

Weeks 12 & 13: Selection of new group leaders and project manager; checking and modification of report.

Weeks 14 & 15: Final report written; editorial review of report; report sent to printer. Oral presentation given to interested persons from industry.

The sequence of conceptual steps through which a design is evolved may be summarized as follows:

1. Gathering of information.
2. Examination of possible configurations, which determines problem areas and generates new ideas and concepts.
3. Estimation of relative merits of the various solutions and determination of trade-off points.
4. Choice of an optimum configuration and final design.

The opportunity for full development of each stage is provided by a breakdown of the course into three phases, described in the table below together with a rough indication of the corresponding stages and group administrations.

<u>Phase</u>	<u>Stage</u>		<u>Adminis- tration</u>	<u>Description</u>
I Formal meetings (1/3 - 1/2 of course)	↑ 1 ↓	↑ 2 ↓	↑ 1 ↓	Formal class meetings--consisting mainly of lectures by experts. The first meeting presents the project topic, ground rules, calls for papers on a rough concept design. After two to three weeks the initial designs are presented and the class organized into groups.
II Group meetings (1/3 of course)	↑ 3 ↓	↓	↓ 2 ↓	Group or individual work, discussion coordination, trade-off sessions, presentation of summary reports at the end of each administration choice of a final configuration.
III Writeup (1/3 - 1/4 of course)	↓	↑ 4 ↓	↑ 3 ↓	Final Design--preparation of final report and oral presentation. Minor changes in the design may still be made if necessary.

#### IV. FINAL PRESENTATION

##### A. FINAL REPORT

Publication of the final report represents the culmination of the efforts of everyone associated with the course. Most students will appreciate this opportunity to publish their contributions. Also, a publishing requirement will tend to improve the ideas and work output of the group.

The first step in organizing the final report is to establish an editorial board at about the middle of the course. This committee maps out the responsibilities for the chapters and submits tentative chapter headings. This process, while seemingly premature, serves to focus the individual effort and permits the group to modify the chapter titles. The committee might also establish a tentative report format at this time.

The editorial board should be made up of volunteers. If each group has an administrative assistant, this student will probably want to be on the board. After the committee has been established, one member should be selected as the editor of the report. Although in the past, the editor has sometimes been the final project manager, this is probably not the best choice since both jobs require full-time effort in the closing weeks.

While the final report is being written, each group leader should pre-edit his group's work before sending it to the editor. Some of this pre-editing and coordinating can be done by the administrative assistant if one has been appointed.

The distribution range of the final report depends ultimately on the funds available for publishing expenses. As a minimum, each participant and each invited speaker should receive a copy. Certainly, the wider the distribution, the more interest by the students in preparing it. It is also suggested that copies be submitted to the following organizations to provide wide distribution:

Defense Documentation Center  
Building 5  
Cameron Station  
Alexandria, Virginia 22314

STAR  
Scientific and Technical Information Division  
NASA  
P.O. Box 33  
College Park, Maryland 20740

International Aerospace Abstracts  
Technical Information Service  
AIAA  
Phillipsburg, New Jersey

#### B. ORAL PRESENTATION

Very few students have the opportunity to present a technical paper. A systems engineering course gives the student this opportunity. The results, obtained by the class, are presented in a one-afternoon conference given to interested members of industries and universities. The guests include all people who have provided information to the class, and anyone else who has shown interest in the project.

The method of presentation is exactly that of a major technical conference. Invitations, describing the program, are sent out a few weeks in advance, practice sessions are held, visual aids are used, and opportunities for a question period are given.

Although it would be ideal to give each student the opportunity to present his results, this is not feasible in a large class. Generally, representatives of the groups and sub-groups are chosen to present the results reached. In past projects, the maximum number of speakers has been limited to between 10 and 15 out of consideration to both the class and the audience.

## V. GRADING

The performance of each student should be based on the following criteria:

1. Performance of his group. This is to be based upon the edited final report and the final verbal presentation. Cooperation among all participants will be essential since only in this way will a smooth version of the report result. The student should be made to understand that while in many of his other courses grades were obtained in competition with other students, cooperation and teamwork are essential ingredients in a systems engineering course.
2. The individual contribution by each student. This may be represented by data gathered, calculations, drawings, analysis, model tests, checking, editing or verbal presentation. In addition, each student should submit, independent of the final report:
  - a. His contribution to the final report, unedited but checked by a member of the group.
  - b. A short statement (two to four pages):
    - (1) Describing his share of the group effort.
    - (2) Describing proposals submitted which were not necessarily included in the final report.
    - (3) Critical comments on the final conclusions.
    - (4) Constructive comments on the overall course.
3. The observations by the staff advisors and consultants to the group. It is recommended that all faculty advisors get together and rate the students relative to each other. Each group advisor should first rate the student with respect to the entire class. For this purpose it might be useful to have a photograph of each student or a seating chart to help correlate names with faces.

As mentioned earlier, a statement of how the final grade is determined should be given to each student at the beginning of the course.

## VI. COST OF PROJECT

The costs of operating a system engineering course based on past experience have been itemized below. The cost that may vary between various institutions such as salaries, staff benefits, and institutional overhead have not been included.

Travel, students and staff	\$1250
Guest Speakers:	
Three Honoraria at \$100	300
Three Travel Expenses	600
Reproduction costs	350
Telephone	500
Final Report--500 copies (includes secretarial time)	<u>2100</u>
TOTAL	\$5100

The staff required to operate such a course is:

One Course Director--about 50 percent time for  
the academic year--advisor  
to 15 students

One additional      --about 25 percent for duration  
Faculty Advisor for of course  
each 15 students

One Full-Time Sec'y--for duration of project, ap-  
proximately 5 secretary-months

The cost of the program as outlined above may be altered and/or defrayed by a number of techniques. One possibility that may be investigated is to secure funds from industry, or a federal government agency that should like to see a particular problem investigated by means of a systems engineering study. Some institutions have affiliate funds established by industry contributions that may be used in place of direct industry support. Industry and government agencies may also support a systems engineering course by supplying technical speakers. This type of assistance would reduce the amount of funds required to secure guest speakers.

Two of the largest items in the proposed budget listed above are the costs connected with the preparation of the final report. Some possible cost reduction in this area is possible by requiring that the first draft of the final report be prepared by the student rather than by a secretary. Another way to reduce the cost of the final report is to require that each student be responsible for the typing of his section of the final report. An alternate to the last suggestion would be the charging of a special course fee. This is done in some institutions in courses that require unusual expenditures.

## VII. NEW IDEAS

The Systems Engineering Course is a relatively recent educational innovation. As such, the general operational procedures associated with it could easily be in a state of flux. The fact that they have not changed appreciably in the four years since the course began is due to the fact that these procedures have been based largely upon successful industrial procedures for preliminary design. Still, since there is always room for improvement in the best of systems, some areas of potential expansion and refinement are discussed below.

One such area is that of inter-university cooperation. This would not only improve the quality of each school's course but would help to reduce the expenses incurred in starting and maintaining such a program. For example, a pair or more of schools could share and/or exchange such things as final written reports, reference books and papers, taped lectures from distinguished guest speakers, and lists of possible class topics. Another possibility would be for smaller schools to serve as "subcontractors" in the design of some of the subsystems that integrate into a system design undertaken by a larger school.

Competition between universities would also prove to be a rewarding experience, as well as providing additional incentive to the students and faculty. Or, this method could be utilized within the same university between different classes. Decisions as to which design is best can be made entirely on the basis of the technical specifications of the design.

A short, clear summary of the results of each design problem is usually worthy of publication in an appropriate technical journal. It would be desirable if all such student papers could be published at the same time in special issues of these publications, possibly in the September issue.

The formation of a national organization to assist in the expansion and development of systems engineering courses is another possibility. A sub-committee of the ASEE (American Society for Engineering Education) could probably serve the needs of the present number of participating schools. Such a committee could aid in the organization of national

student conferences and short summer staff conferences. It could also coordinate publication of papers and special issues of the technical journals.

Another desirable program might be to arrange a one or two week symposium on a topic of national interest such as the smog problem. Such a symposium might be arranged by the Commission on Engineering Education with the aid of one of the federal agencies about late August. Such a symposium attended by the faculty advisors who are planning a system study in the field (smog control) would make it possible for the top experts in the country to present their viewpoints to many universities as a starting point for new system studies. During the school year various universities might carry out their own system studies and hopefully come up with technical recommendations. It would be useful then to have another one or two day follow-up meeting about June at which the conclusions and recommendations are presented to the government organization which sponsored the initial meeting.

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## APPENDIX A

### Initial Course Announcement, Describing the Over-All Plan of the Course At MIT (1962-1963)

by William Bollay

It is the goal of this course to give students experience in and an appreciation of the over-all problems involved in carrying out the preliminary design phase of a typical complex engineering system while at the same time permitting them to examine in considerable detail one particular aspect of the system. In order to achieve these two goals it is anticipated that the class will spend approximately one half of the total course time (1/2 of 180 hours) becoming acquainted with the over-all system. Through lectures, study of material related to the lectures, and solution of a few simple problems designed to illustrate the basic principles involved, each student should obtain a familiarity with the basic factors influencing the design of all the major subsystems and the manner in which they interact.

The remaining half of the scheduled course time will be devoted to carrying out a preliminary design of the weather satellite system. This Part II, designated as Project Work, will be carried on concurrently with the program outlined above and will begin with the formulation of a set of requirements and specifications for a system which is technically feasible and economically desirable and end with a preliminary design for the system. For this phase of the work it is proposed to organize the class into small project groups and to carry out the over-all design on a team basis in much the same manner as it would be done in industry. Each project team will decide on the alternatives to be studied and how to divide the work into sub-projects.

Each student will prepare three reports:

1. A preliminary report of specifications for the subsystem which he selected for analysis and a comparison with alternatives (due March 19)
2. Preliminary engineering report on his subsystem (due April 23)
3. Final engineering report (less than 20 pages) on his subsystem (due May 16).

In addition he will check the reports of one of his classmates, and through coordination with the other members of the class, participate in the over-all planning and decision making processes.

A total of thirty-six lectures are planned during the semester. About half of these are by the M.I.T. staff and concentrate on the fundamental principles involved in the various technologies of a weather satellite system. The other half of the lectures are by outstanding engineers from industry and government and present a summary of the current state of the art in the various technologies, and projection of this state of the art into the future, and a presentation of interesting and pertinent problems affecting the design of a weather satellite system.

It is planned that the class undertake the preliminary design of a major engineering system. In order to make this problem as realistic as possible, it is proposed to undertake the engineering of a system which appears to be technically feasible and operationally desirable but which has not yet been designed or built by industry.

Specifically it is proposed to undertake the design of an alternate equatorial weather satellite system.

In order to undertake this design it is proposed that the class organize itself into the following project groups:

1. Launch facilities - (missile transport; launcher complex; launch checkout system and instrumentation system)

This group will explore the technical design problems and the relative merits of launching the equatorial satellite from a ship, barge, or island near the equator, taking realistic account of the additional instrumentation and launching facilities involved versus launching from Cape Canaveral which involves a large booster size penalty due to a "dog-leg" trajectory involved in order to attain an equatorial orbit.

2. Booster system - (rocket design, aerodynamics, structures, thermal design, guidance and control system; stage separation and dynamics)

This group will undertake the technical design of a multi-stage solid propellant rocket booster\* and compare it with the alternative of using one of the current IRBM or ICBM boosters. (Only unclassified published data will be used for these IRBM and ICBM boosters.) The comparison of liquid vs. solid propellant boosters for this mission will include the relative costs, availability, and reliability, as well as the related launching facilities and equipment.

3. Satellite system - (TV, IR, radar sensors, integration of communication system, power supply system, data storage and readout system, stabilization system, structural and thermal design)

This group will select the most promising sensor systems and the power supply and together with Group 4 select the communication system. An early system (for use 1965-1970) will be designed and a second generation system (for use in 1970-1980) will be recommended for research and development with preliminary estimates on performance potentialities. An important decision will be whether to use only TV and IR systems in the first generation system or whether to include also communication relay from ocean based transmitters or floating balloons. The other critical decision will be in the selection of a stabilization system. The Nimbus system has been delayed by the complexity of its stabilization system. Alternate

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\*The students may also select a liquid or hybrid propellant rocket system but will need to show that such a system has advantages from the standpoint of relative costs, availability and reliability.

possibilities are to use a spinning satellite with spin axis parallel to the Earth's polar axis, or to use gravity-gradient stabilization taking advantage of the "dumb-bell effect." Each of these has other problems which need to be analyzed quantitatively in order to reach a technical decision. This satellite design group will probably be divided into a number of subgroups in order to distribute the work more evenly.

#### 4. Communication system

This group will be responsible for the satellite and ground based portions of the communication system. The group will also design two types of ground stations--one for the direct readout of the weather data for purposes of local weather forecasting, and a second station for delayed readout at a central facility for purposes of tropical weather research. Ideally the direct readout station would consist of the simplest equipment (Yagi array, receiver and facsimile recorder) and would be automatic without command. The group will recognize that the delayed readout system should be consistent with the Nimbus and Aeros requirements whenever feasible.

#### 5. Data processing system

This group will study the total data processing system both for local weather forecasting purposes, and for more general meteorological use in connection with tropical weather research and the use of numerical weather forecasting systems. New ideas in this field are badly needed, and may represent an important contribution to the design of a weather satellite system.

#### 6. Project management (including Industrial Management)

A small project management group will coordinate the over-all study, setting time schedules for the study and also preparing a schedule for the development of the complete system including estimates of time and costs.

Each of the first five groups will select one of their members as group project engineer and another member as assistant group project engineer. The positions will be rotated every four weeks, the assistant group project engineer advancing to project engineer. The group project engineer and assistant group project engineer represent their groups in the project management group. One of the five group project engineers will be selected as project manager. One of the five assistant group project engineers will be selected as assistant project manager. The project management group will have the responsibility of making decisions on the many trade-offs which are involved in the over-all system. Their decisions and the reasons for these decisions will be reviewed before the whole class. A selected group of students in industrial management will support the project management group in planning and scheduling and cost estimating.

# MIT and Stanford projects in system engineering—an educational experience in creative design

William Bollay

SOME EXPERIMENTAL PROJECT courses have been conducted during the past 4 years at MIT and Stanford University in the design of relatively complex engineering systems. These projects utilized teams of graduate students from many disciplines of engineering supervised by faculty advisors and assisted by outstanding lecturers from industry and government.

Participation in these system-engineering projects has proven to be highly rewarding for the participating faculty and for students. These projects turned out to be an excellent way for finding unsolved technical problems on the frontiers of technology. These unsolved problems provided opportunities to find useful engineering research topics for the graduate students and to exercise ingenuity in the design of clever solutions for these unsolved problems.

Such a system-engineering project does not replace the conventional courses in circuit design, mechanical design, etc. Rather, the project supplements these courses: they give the students a chance to formulate their own technical problem as a part of a major system to supply human needs. This accurate formulation of the technical problem in the light of all the complex and conflicting requirements of real life is an important first step to the solution. The proverb that "A problem well put is a problem half solved" applies to technical as well as human problems.

## Introduction

During the past 20 years, U.S. schools of engineering have quite properly reoriented their curricula to teach the fundamental principles of the sciences basic to engineering. Also they have quite properly increased their emphasis on engineering research to gain better understanding of engineering materials, processes, and phenomena. In this reorientation, the creative aspects of engineering new devices and products useful to man have, however, tended to be suppressed.

The question of how to teach creative engineering in the current academic environment is one which has concerned many engineering faculties. The problem is somewhat similar to that involved in teaching scientific or technical research. Giving lectures on how to do research has been found to be a sterile business. The only effective means which has been found to date is to have the students participate in a research project with a competent and inspiring teacher. Similarly it seems that the only effective method for teaching creative engineering is for the students to take part in creative engineering-design projects.

The question then comes up whether the student can acquire this learning experience in creative engineering design at the university. In principle, it could be carried out either at the university or in industry in the same way as a student could learn to do research either at the university or industry. Each has advantages and disadvantages. This paper describes an experiment which has been conducted at MIT and Stanford University during the past 4 years; the aim has been to explore the

potentialities of carrying out such system-engineering studies at a university as an interdisciplinary course for a large class of graduate students of science and engineering. This program was started in 1962 at MIT and in 1963 at Stanford University. Both of these programs are continuing. This report describes some of the lessons learned, particularly from the standpoint of stimulating faculty and students to think in terms of innovation and creative engineering.

## First step in innovation: find a need for a new device

To teach creative engineering, the first critical consideration as in all invention is to find a problem which requires solution. Then the problem with all of its essential boundary conditions must be clearly and accurately formulated.

How do we find these well formulated problems at the universities? Should the universities count upon industry to find and formulate their problems and present them to the students? This can hardly be expected. For industry would normally not only formulate its problems but would also ordinarily solve those which are tractable. Thus, at the most, only the intractable problems would be referred to the university; these would not ordinarily provide promising subject matter to encourage students and faculty in creative design.

Or should the students only rework old problems with known solutions? Students can learn many excellent engineering lessons from old problems presented in an instructive manner, step-by-step, as the engineer actually experienced the situation. Such case studies to teach engineering design are being developed at Stanford and at other engineering schools. This technique appears to be as promising for teaching engineering as it has been in the schools of law, medicine, and business administration. And old problems have the advantage of a known solution.

As a supplement to case study, the student of engineering should have at least one short exposure to a real-life situation: He must find and formulate his own problem as a partial solution to a complex overall need. Such an experience is usually faced by the chief engineer of any company. He must anticipate the future trend of development and initiate his own studies—both to find hardware items to develop and also to prepare his company for future system-development projects.

It is an excellent experience for a student of engineering to participate in a stimulating design study while he is still at the university. First of all, this is the period of his life when he is most creative. Thus he is more likely to come up with a significant new approach than when he has been conditioned by experience to be more cautious and conventional. Secondly, if he has a talent for innovation he has an opportunity to taste the thrill involved in this phase of engineering; thus he is more likely to become an innovative engineer than an analyst or administrator.

In aeronautics and astronautics, the opportunities for major new innovations occur mainly on the frontiers of the technology. These opportunities are usually found by

making a broad system study and searching for ways and means of using the new technology as a better method for satisfying human needs. For example, current space technology makes it feasible to have earth satellites observe and relay data about events over the entire surface of the earth. Moreover, these functions can be performed economically and reliably by taking advantage of the microminiaturized computers which are currently being developed. A careful system study is required, however, before these general potentialities can be converted into an automatic weather-forecasting system.

#### One approach to the teaching of system engineering

Most universities are organized for administrative reasons along the lines of the traditional technologies—mechanical engineering, electrical engineering, chemical engineering, etc. Similarly, in industry the engineering departments are usually organized along functional lines. To undertake the study or preliminary design of any major new system, industry has found it essential to organize multidisciplinary teams of engineers and scientists. It appears that the same approach is necessary at the universities. In industry each of the participants of such a multidisciplinary team is usually an outstanding engineer in his own field. Ideally, he should be inventive and innovative with a superior understanding in his own technology and a reasonable understanding of the fundamentals in the neighboring disciplines. In addition, he should be cooperative in working with other members of the team and this involves traits of character which are as important as technical excellence.

The following approach was used at MIT in 1962-63 and at Stanford during the past 2 years. Three to five professors from such fields as aero-astronautics, instrumentation engineering, mechanical engineering, electrical engineering, and industrial engineering served as faculty advisors to the class. One of the professors was overall organizer and coordinator of the project. The advisors selected a class project which met the specifications that it represent a complex engineering system not yet designed nor in existence but which gives promise that it could be designed with the current technology and which would satisfy an important need of society.

The projects and the faculty advisors were as follows:

	Project Organizer	Other Faculty Advisors
<b>MIT (1962-63)</b> Equatorial Weather-Satellite System	W. Bollay	D. N. B. Baumann Y. T. Li Rene Miller W. W. Seifert
<b>Stanford University (1963-64)</b> Weather Data-Collection System (as a basis for an automatic weather-forecasting system)	W. Bollay	R. H. Cannon, Jr. Bruce B. Lusignan

Each of these projects has been successful and viable. The MIT projects are being continued under the direction of Professors W. W. Seifert and Rene Miller. Professor Seifert managed a project during 1963-64 on an advanced orbiting observatory. During the spring of 1965, two projects were under way at MIT—one under Professor Seifert on a high-speed transport system between

Boston and Washington, D. C., and one under Professor Miller on a manned Mars exploration system.

At Stanford, the project continued during 1965 under the management of Professor Lusignan on an unmanned Mars exploration system.

The sizes of the classes have varied from 30 to 60 students. Most of them have been graduate students from engineering and science. In addition, a few students from such departments as English and philosophy have participated on the editorial, planning, and evaluation functions. The course duration has been one semester at MIT and two quarters at Stanford.

About half of the lectures, dealing with fundamental principles, were given by the academic staff of the university; the other half, dealing with the state-of-the-art of the technology, were given by engineers from industry and government. The students devoted 12 hours per week to this project (two afternoons of 3 hours each in class and 6 hours per week to direct project work). They organized the work under student group leaders of their own choosing and changed group leaders every 4 weeks to provide the opportunity for project management to a large percentage of the students. One student served as project manager for each 4-week period.

At the conclusion of the study, the students presented a 3-hour briefing of their conclusions to leaders from industry and government including the lecturers who had initially contributed to the course. In addition, they published a report of about 300 pages summarizing the conclusions and recommendations of their studies.

#### What benefits?

Most of the students in these courses indicated that they gained an excellent appreciation of what is involved in the engineering of a real system. The course strongly motivated them to dig into the literature and find out about the current state of the art of the technology in their own fields and the advantages and shortcomings of the various alternatives from the standpoint of the overall system. This critical search for an analysis and evaluation of the current technical approaches usually served as the first step in the development of an improved system. By having to defend their inventions, students sharpened these new concepts considerably before the semester ended.

Some of the interesting ideas which were generated:

*MIT equatorial weather-satellite system:* It was concluded that a simple gravity-gradient stabilized satellite in a circular orbit at a height of about 2,500 nautical miles would provide a direct readout of the earth's cloud system over the equatorial belt of the earth from  $-30^\circ$  to  $+30^\circ$  latitude. Three such satellites weighing about 200 pounds each would provide a cloud picture every hour. The picture covered an area of about 4,000 by 6,000 miles. One of the innovations was a simple line-scan TV system along north-south lines. This trick in association with the equatorial orbit greatly facilitated design of the direct readout and rectification system. As a result, the ground station was simple enough so that it could be used on any ship at sea or in any of the underdeveloped countries around the equatorial belt where hurricanes are a threat. Other innovations included a

cerium 144 nuclear-power generator and a mobile-silo sea-launch system.

*Stanford data-collection satellite:* It was concluded that a system of three satellites weighing about 400 pounds each, either in 120° spaced polar orbits or in mutually orthogonal polar and equatorial orbits, at a height of about 1,200 nautical miles, would provide an ideal method for the collection of weather data from automatic stations on land, on buoys at sea, or on constant-pressure balloons. Such a system would provide the inputs required by a ground-based digital computer for integrating the equations of motion of the atmosphere. This computer could thus constantly provide an automatic updated forecast of major weather patterns. Some of the detailed design concepts which required innovation and creative engineering involved a satellite-borne

computer which could determine the position of the constant-pressure balloons. Further, from the change in position with time, the computer could determine the wind at these various locations. The booster design also included a new method for the control of large solid-propellant rockets when used in a cluster arrangement. The launch system proposed was a novel use of the FLIP (Floating Instrumented Platform).

In addition to these new design concepts, another useful contribution was the formulation of one of the critical problems—a means of measuring the mean temperature of a layer of air. As a result of this problem formulation by the Stanford class, one of the visiting lecturers, Professor V. E. Suomi of the University of Wisconsin, was stimulated to work out an ingenious solution with some of his graduate students.

## APPENDIX C

### THE SPACE SYSTEMS ENGINEERING COURSE AT STANFORD UNIVERSITY

by

B. B. LUSIGNAN\*

Stanford University, Stanford, California (U.S.A.)

#### 1. Introduction

The Space Systems Engineering course taught at Stanford is similar in most respects to that taught at MIT and described by Professor HALFMAN in the previous paper. The course was first taught at Stanford in the winter and spring of 1964. It was directed that year by Dr. William BOLLAY who had helped organize the MIT course the previous year. Students at Stanford, as at MIT, have responded favorably to the course—in fact, at Stanford the enrollment doubled from 25 to 50 students in the two years the course has been offered. Considered experimental during the first two years, the course is now a permanent part of Stanford's engineering curriculum.

The general format of the course and the benefits the students derive from it have been amply described by Prof. HALFMAN. I, therefore, will not dwell on these aspects of the course. Rather, I will describe in some detail the outcome of the 1965 project at Stanford, the design of an unmanned Mars exploration vehicle. In doing this I will try to illustrate the various benefits derived from the course. The high quality of the final design illustrates that the students have indeed formed an effective design team. Some of the concepts devised by the students make real contributions to the actual space system. These contributions illustrate the importance of one of the major skills taught by the course—that of communicating with engineers and scientists of widely varying backgrounds.

We find that studies by the student teams both at MIT and Stanford has resulted in final designs that are equivalent in quality to studies performed by industrial teams. Several things contribute to this result. First, the student teams have as many, and sometimes more, people working on the study than an industrial team would have for a similar project. The academic

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\* Assistant Professor of Electrical Engineering.

Table 1

## List of guest speakers for Mars exploration study

Lecturer	Topic
<b>A. Visiting lecturers</b>	
Der Garabedian, Mr. Paul Space Technology Laboratories	Upper stage and braking rockets
Dessler, Dr. Alexander J., Head Space Science Department Rice University	Particle detectors
Eckman, Dr. Philip Jet Propulsion Laboratory	Communications with a Mars vehicle
Elizalde, Mr. Juan C. Spacecraft Heat Transfer Dept. Space Technology Laboratories	In-flight propellant storage
Gingrich, Dr. James E. Atomics International	Radioisotope power supplies
Gradecak, Mr. Vjekoslav Future Project Office NASA-Marshall Space Flight Center	Saturn rocket systems
Grosser, Dr. Morton Boeing Scientific Research Labs	Technical writing
Hornby, Mr. Harry NASA-Ames Research Center	Manned exploration of Mars
Klein, Dr. Harold NASA-Ames Research Center	The Mars mission: problems involved in life detection
Masursky, Dr. Harold Lunar and Planetary Studies U.S. Geological Survey	Martian geology
McMurtry, Dr. Burton Optics Department Sylvania Electronic Systems	Lasers for space communications
Neustein, Dr. Joseph Electro-Optical Systems, Inc.	Spacecraft power supplies
Newman, Dr. Temple Aeronutronics, Inc.	The automated biological laboratory
Peery, Dr. David General Dynamics/Astronautics	Atlas/Centaur rocket systems
Pickering, Dr. William H., Head Jet Propulsion Laboratory	The Mars mission
Reese, Mr. David E., Jr. Vehicle Environment Division NASA-Ames Research Center	Definition of the Mars atmosphere from entry vehicle measurements
Schneyer, Mr. Raymond Lockheed Missiles and Space Co.	Decontamination of a Mars probe
Smith, Mr. Gordon Autonetics Division North American Aviation, Inc.	Aerospace computers

Table 1 (cont.)

Lecturer	Topic
Smith, Dr. Richard United Technology Corporation	Solid propellant rocket systems
Sohn, Dr. Robert Space Technology Laboratories	The Mars mission
Sonnett, Dr. Charles Space Science Division NASA-Ames Research Center	Magnetic field measurements
Spencer, Mr. Dwain F. Engineering Mechanics Div. Jet Propulsion Laboratory	Approaching the problem of an unmanned landing on Mars
Spinrad, Dr. Hyron Dept. of Astronomy U. of California, Berkeley	The planet Mars
Syverson, Dr. Clarence A. Mission Analysis Division NASA-Ames Research Center	Manned Mars missions and their effect on unmanned missions
Worth, Mr. Robert Northrop Space Laboratories	Early Mars mission descent and landing system
<b>B. Stanford staff lecturers</b>	
Bollay, Prof. William Dept. of Aeronautics/Astronautics	Introduction to trajectory and propulsion
Breakwell, Dr. John V. Dept. of Aeronautics/Astronautics	Mars orbit analysis
DeBra, Dr. Daniel Dept. of Electrical engineering	Spin stabilization
Eshleman, Prof. Von R. Dept. of Electrical Engineering	Radar determination of the Martian atmosphere
Garriott, Prof. Owen K. Dept. of Electrical Engineering (NASA Scientist-Astronaut)	Radio propagation measurements of interplanetary and planetary electron concentrations
Lederberg, Prof. Joshua Exec. Head, Dept. of Genetics Professor, Dept. of Biology	Planetary life
Levinthal, Dr. Elliott Dept. of Genetics	The multivator life sensors
Lusignan, Prof. Bruce B. Dept. of Electrical Engineering	Introduction to communications
Seifert, Prof. Howard Dept. of Aeronautics/Astronautics	Electric propulsion systems

training of the student team is perhaps slightly higher and certainly more recent; about a third of the team have Master's degrees, while the rest have at least Bachelor's degrees. In addition, three or four faculty members contribute to the effort.

The principal deficiency in the student team is, of course, in the area of experience. Over half of the students have never worked in industry, and of those who have, most have had only summer job experience. To compensate for this lack of student experience, the most experienced people in the pertinent fields are invited to give one-hour briefings to the class. The leading experts in the space field have been very helpful in supplying the students with the necessary information. The success of the course and the quality of the resulting design is due in a large part to such enthusiastic cooperation by these experts. A list of guest speakers who contributed to last year's Mars exploration study is given in Table 1.

## 2. Sampler: A Mars Exploration System

The following description is of necessity superficial. The complete details of the Sampler design are to be found in the 500 page final report on Sampler, written by the class and published by the School of Engineering of Stanford University.

The final mission designed for a 1971 launch consists of two identical landing vehicles and one orbiting vehicle to be launched by a Saturn 1B/Centaur rocket system. The total payload weight is 7585 lb, considerably below the capabilities of this launch system for a Mars trajectory. This will allow the system, or a slightly modified version of the system, to be launched for the 1973 Mars opportunity. In 1971 the extra capability allows choice of a trajectory that gives a shorter transfer time from Earth to Mars, thus increasing the reliability; a shorter communications distance, thus increasing the information rate; and an earlier time of arrival, putting the life detecting experiments on the surface of Mars at the height of the wave of darkening (Mars' spring), rather than in Mars' summer when the possibility of detecting life is probably lowest. Although the rocket would most likely be available for a 1969 launch, it was decided that the development time for the landing vehicles would not permit this and a test shot of the orbiter alone was recommended. A weight breakdown of the Sampler system is shown in Table 2.

Table 2  
Weight breakdown of the Sampler system

1 midcourse motor	300 lb
2 landers at 1655 lb each	3310
1 orbiter	1475
Retro-rocket (1.2 times orbiter weight for November 1 arrival)	1800
Cylinder to contain lander capsules	700
Total approximate weight	7585 lb

Figure 1 shows an artist's conception of the Sampler lander. The lander is separated from the main vehicle about a week before arrival at the planet. It is deflected to an impact course with the planet by a small rocket and its entry velocity is initially reduced by atmospheric braking. The heat shield which protects the main instruments is separated after the velocity goes below Mach 1 and a parachute is deployed to slow the descent further. The lander is cushioned against final impact velocities up to 90 mph by 18 in. of crushable aluminum honeycomb on its bottom and sides. After impact, the lander opens up as shown in the illustration. Power is supplied to the lander by a 35 W radio-thermal generator which also supplies 665 W of thermal power to control the lander temperature in the cold Martian environment. Communications are made directly to Earth at a rate of 5 bits per second (bps) with a 4 W, 2.3 GHz transmitter or by relaying through the orbiter at 5000 bps with 15 W at 300 MHz. The orbiter is commanded at a 10 bps rate directly from Earth. The vehicle has a designed lifetime after landing of greater than 6 months.

The experiments carried by the lander are listed in Table 3.

Table 3  
Experiments carried by the lander

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Geological
Television
Atmospheric measurements
Determination of surface characteristics
Inference of internal structure
Biological
Gaseous and liquid composition of the surface
Organic composition of the surface
Inorganic constituents of organic matter
Presence of amino acids, sugars, porphyrins, nitrogenous bases, and aliphatic hydrocarbons
Photosynthesis and respiration
Utilization of carbohydrates by organisms
Enzymic activity

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At the time the students did their study, there was much discussion in NASA planning groups over whether an Automated Biological Laboratory (ABL) should be included in the first Mars lander. Although no detailed design of such a laboratory had been completed at that time, it was felt that a Saturn IB payload was inadequate for such an instrument. One of the students' major contributions to the actual Mars exploration is a detailed design of an integrated biological laboratory. The design was carried out

in more detail than is normal on a preliminary design study because of the newness of this concept. The two biology students and two engineering students who produced this design conclusively illustrate the need for communication between specialists in different areas. The final weight estimate for the biological laboratory is 67 lb (see Table 4), which agrees well with recent designs of an ABL by Dr. Joshua LEDERBERG.

Table 4  
Weight breakdown for biological laboratory

Item	lb
Sampler (total)	7
Ovens	2
(2) Gas chromatographs, 7 lb. ea.	14
(2) Mass spectrometers, 2 lb. ea.	4
Culture chambers	5
Photosynthesis chambers	5
Chemistry	20
Optical spectrometer	10
Total approximate weight	67 lb

Table 5  
Weight breakdown of entire lander

Lander	lb
Scientific payload	160
Power supply	80
Environmental control	30
Communications	25
Data processing	5
Structure	260
Impact attenuation	190
Lander weight	750
Parachute	125
Heat Shield	745
Entry weight	1620
Separation System	
Deflection rocket	30
Spin rockets	15
Separation system weight	45
Lander system weight	1665

In addition to producing a realistic laboratory design, the course has also contributed to the space effort by producing biologists who really know the practical engineering constraints of Mars exploration.

Figure 2 shows the orbiting vehicle using a solid retro-rocket to slow it down and establish an orbit about Mars. This vehicle carries a normal complement of interplanetary experiments as well as a full complement of planetary mapping and radiation experiments (see Table 6).

Table 6  
Experiments aboard orbiting vehicle

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Compartment I
Photographic mapper and IR sensors
Compartment II
Magnetic field
Cosmic ray
Cosmic dust
Bistatic radar
Topside R sounder
Communications
Mounted at focus of 18-ft antenna
Gamma ray spectrometer and high energy particle detector
Solar plasma
Cosmic dust and cosmic ray

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The principal planetary experiment is photographic mapping. The system chosen is a wet film developing system similar to that used in the Russian lunar photography experiments and the American Lunar Orbiter program. The Sampler orbiter is capable of mapping the entire surface of Mars to a resolution of about 30 m (100 ft). This it does through three different colored filters and in addition does lower resolution, infrared mapping of the planet. The orbiter is stabilized inertially using either the radio beacon from the Earth or the Sun and either of the stars, Canopus or Capella, as reference directions. As a back-up, the spacecraft can be spun slowly and stabilized by command from Earth using any one of eight possible gas jets.

Figure 3 shows the entire space vehicle just as one of the landing vehicles is being ejected from the main spacecraft. Both landers are carried inside a canister. The sealed canister and two landers are heat sterilized before launch. In the illustration, the top of the canister can be seen drifting away while the one lander in its heat shield has just been released. The second lander is still within the canister. After the second lander is released and put on an impact trajectory to Mars, the remaining part of the canister is ejected from the launch vehicle. The midcourse correction rocket can be seen

mounted on the top of the sterilization canister, canted to thrust through the center of gravity of the entire assembly. More details of the orbiting vehicle can be seen in this position. As is apparent, the orbiter consists primarily of an 18-ft diam, parabolic reflector. The compartment at the focus of the parabola contains antenna feeds and those experiments that need direct access to the solar plasma without shadowing by spacecraft structure.

This figure also clearly illustrates probably the major contribution of this year's class study to space technology. The Sampler orbiter vehicle is capable of transmitting information from Mars at a rate of 250,000 bps. It is this bit rate that allows the very high resolution mapping of the Martian surface and transmission of surface television pictures from the lander back to earth. This high bit rate is more than 3000 times the rate of the recent Mariner IV spacecraft and more than 25 times the rates quoted for early designs of Voyager (1971 NASA Mars exploration vehicle). The key to this high bit rate is, of course, the 18-ft antenna. The chief contribution by the students is that they have devised a way to include in a single structure both the large antenna and the necessary solar cell power supply. This is done, as shown in the figure, by coating the parabolic surface with the solar cells of the electrical power supply. The antenna then is oriented toward the Earth which causes some loss of power to the solar cells since the Sun's rays will no longer shine directly on them. However, from Mars the difference in directions to the Earth and to the Sun never exceeds  $47^\circ$ , giving at worst a loss in spacecraft power of 30%. The area of the dish is more than enough to provide power sufficient to compensate for this loss. By combining these two systems into a single structure, it is possible to have the large antenna while maintaining a simple spacecraft design. There are no deployable solar panels or booms on the Sampler orbiter. The required pointing accuracy for the antenna is about  $1^\circ$ , well within the requirements of even the Mariner spacecraft.

The main source of worry with this concept was the possibility that the solar cells would interfere with the radio characteristics of the antenna. Although the surface roughness introduced by the cells was well within the tolerances of any antenna, the worry was that the solar cell semiconductor material would absorb the radio energy and thus reduce the amount transmitted. The students found theoretically that the radio "skin depth" of the solar cells was much greater than the actual thickness of the cells. Therefore the radio energy should penetrate to the solder backing of the cells and be completely reflected rather than absorbed. Calculations also showed that this process caused no appreciable phase shift of the reflected radio energy. To confirm the theoretical results, the students mounted a panel of solar cells at the end of a waveguide and actually measured the reflectivity coef-

ficient of the panel. It was found that the experimental results agreed with predictions and the radio reflectivity of the solar cells was no problem at all.

This contribution to space technology came directly from the communication between engineering students of different backgrounds. Initially electrical engineers from the d.c. (power supply) end of the spectrum and from the radio frequency end of the spectrum had to talk together. The trajectory analysis engineers realized that the Earth-Mars-Sun angle never became large enough to reduce the solar-cell power output seriously. The engineers responsible for stabilization of the spacecraft found the pointing requirements for the large antenna well within present capabilities; and finally, the mechanical designers realized the enormous simplification of the spacecraft design that would result if the solar power supply and the antenna could be combined.

*Although each individual who contributed had the answers to his particular part of the question, the new concepts would not have evolved if the engineers had not been working together as a team. It was the ability to communicate with, to understand, engineers and scientists in other fields that led to the new innovations in the systems design. The mechanical engineers, electrical engineers, industrial engineers, aeronautical engineers and the biologists that participated in this course are now able to talk to and understand each other. They can explain their ideas and in turn understand the ideas of their fellow designers and they realize the very great importance of such communication in a system design study. The quality of the Sampler study bears witness to the importance of these concepts and to the ability of the approach used at Stanford and at MIT to teach them.*

### 3. The 1966 Study

The subject of the 1966 Stanford Space Systems Engineering course is the World Weather System. The goal of the project is to prepare a preliminary design of an international weather forecasting system which takes full advantage of potentially available satellite and computer technology. The study will include analysis and preliminary design of satellites, sensors, ground equipment, forecasting computer programs, and studies of political and economic factors. The Stanford design team will include from 40 to 60 graduate students from electrical, mechanical, aeronautical, and industrial engineering, business, economics, and political science. Since this study will include international aspects of this worldwide problem, the participation of qualified foreign students from developed and underdeveloped countries, from the eastern and western parts of the world, will be encouraged.

Background information on satellite technology, meteorology, and political and economic factors will be supplied by over 25 guest speakers from American and foreign universities, government, and space industries. Additional information will come from field trips to nearby facilities.

#### 4. Summary

Stanford's experience with the Systems Engineering course has been highly rewarding to both students and faculty. Based on this experience, we would strongly recommend that other engineering schools try this type of course if they are not presently doing so. The initial organization, financing, and teaching of such a course is not straightforward and we have modified and improved our approach through the years. If it would prove helpful to other schools to start such a course, we would be glad to forward to them the details of our present course organization on request.

There would be advantages to having several schools in various countries conducting such courses study the same topic simultaneously (i.e. design the same or perhaps different aspects of the same system) and exchange information on their progress. This would be an effective means of exchanging scientific information and establishing communications between the young generation of scientists and engineers. It would make a wider range of speakers available to the individual courses by recording talks given at one university and mailing these recordings and associated slides to the other participating schools. And finally, by choosing a topic of real international interest, realistic system studies would be obtained that would reflect and perhaps reconcile the viewpoints of several countries. If cooperation of this sort proves feasible, Stanford would be happy to participate in such a program.



Fig. 1. Artist's conception of the Sampler lander

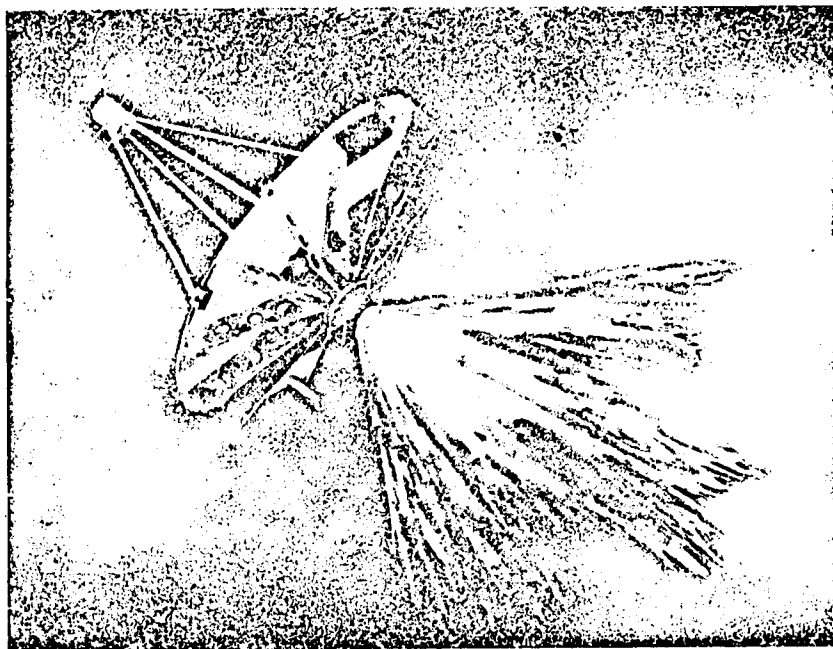
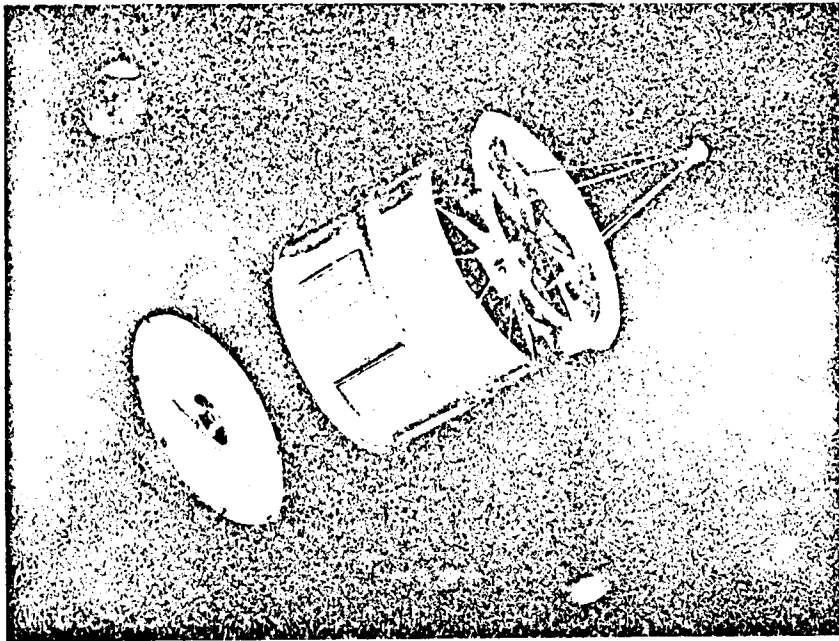


Fig. 2. Orbiting vehicle using a solid retro-rocket to slow it down and establish an orbit about Mars



**Fig. 3. Sampler orbit ejecting one of the landing vehicles**

## APPENDIX D

### SYSTEMS DESIGN—A TEAM EFFORT

by

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#### Abstract

To acquaint fourth and fifth year students with the problems and practice of creative engineering of complex systems, the faculty in Aeronautics and Astronautics at Massachusetts Institute of Technology has developed a very successful course in Systems Design. With cooperation from students and faculty from other Departments and from experts from industry and government, the students organize into a team effort with a project leader and subsidiary groups to provide specialized support. With student initiative and enthusiastic faculty support, an integrated design slowly and haltingly takes shape with progress strongly dependent on adequate intercommunication, the identification of key parameters, and responsible and timely effort. The process is illustrated by excerpts from the recent Manned Mission to Mars.

By the time a student has finished his undergraduate work in a modern curriculum in an engineering discipline such as astronautics, he has acquired certain skills and background. His knowledge is firmly based on science; that is, his methods are derived from fundamental principles with little of the empiricism so familiar to students of the handbook era of engineering. He has knowledge of and some skill with a wide range of sophisticated and elegant mathematical techniques and tools. He is accustomed to solving explicit problems in which the transition from physical reality to mathematical form has largely been done for him and for which there are distinct and clearly correct answers. He seldom is required to interpret such answers in the context of a much larger and more difficult problem, and can usually neglect the interaction of his analysis with those of others.

These distortions and shortcomings in the undergraduate education of an engineer are not easily avoided. Before he can learn to practice engineering with all its elements of judgment and intuition he must learn the manipulation of the tools of the trade. Thus he must concentrate on the analytical techniques, on the isolated fundamental principles, on the clearly-stated illustrative problems. He must understand the essentials of the basic disciplines before he can begin to appreciate their interactions and interrelationships.

To acquaint the student with the problems and practice of creative engineering the faculty in Aeronautics and Astronautics at the Massachusetts Institute of Technology has developed a course in Systems Engineering. This course requires about one-quarter of a student's effort over a half of an academic year and is available to fourth year and post-graduate students.

During the year 1962-63 the students completed a preliminary design and feasibility study of an Equatorial Weather Satellite System. The following year the subject was an Advanced Orbital Astronomical Observatory. This past year the project was the preliminary design study of a Manned Mission to Mars.

These projects may seem too ambitious but in fact were eminently successful. There was participation from students and faculty in other departments of M.I.T. such as Civil, Electrical, Mechanical and Nuclear Engineering. The students organized on a team basis with a project leader and subsidiary groups to provide specialized support. The specialists had wide scope for creative and original effort but always within the context of the project. The overall success was soon found by the students to depend rather strongly on the effectiveness of their intercommunications rather than simply on their individual brilliance. The absence of unique solutions to the larger problems, the need for identifying key parameters, the give and take so necessary to optimization of the design, the adaptation of analytical techniques to physical problems rather than the reverse, all these ideas and more became painfully obvious to the students. Simultaneously came the enthusiasm and satisfaction of discovering that they were capable of making significant progress on their own.

To enrich this process and to insure completion within the limited time of four months, half a dozen members of the faculty presented background lectures and were readily available for consultation. Outstanding scientists and engineers from industry and government were invited to lecture on the state of the art in particular areas of interest. Usually

the interchange between expert and students was dynamic, stimulating and rewarding to both. Much of the success of the entire course is rooted in the obvious enthusiasm of the students in exploiting the freedom from detailed constraints and in doing it responsibly. They were limited not so much by the faculty as by the inherent practical conflicts leading to design compromises.

In order to illustrate the scope of the course, the recent Manned Mission to Mars will be used. Thirty two students drawn from three M.I.T. Departments were organized according to their interests and abilities into groups and assigned responsibility for major subsystems; communications, data processing and display; guidance, navigation and trajectories; propulsion and power; spacecraft; system integration.

The results of their work were presented orally in a frank and stimulating fashion complete with slides and scale models to an audience drawn from industry, government and education. A more complete report was written and published by the students in a volume of over 300 pages. The range and variety of their efforts can be estimated from the Table of Contents of the report which is reproduced in reduced form as Table I. The sub-heading Mars Excursion Module under the chapter heading Spacecraft has the further content indicated in Table II. The spirit of the overall mission can be glimpsed in the following quotation from the final report.

#### "Mission Profile

The mission launch window occurs in August, 1983. The 1984 opposition was selected for the mission because it offers

TABLE I

1. Summary	8. Communications
2. Introduction—Mission Definition	Design Considerations
Costs	System Configuration
Mission Profile	Communications System Design
3. Trajectories	System Size, Weight and
Interplanetary Trajectories	Power Estimates
Parking orbits	9. Experimentation
Abort Possibilities	Basic Considerations
4. Propulsion Systems	Preliminary Task Analysis
Primary Propulsion	Detailed Task Analysis
Propellant Management	10. Crew Utilization
Auxiliary Propulsion System	Size
System Weight	Organization
Cost	Tasks
5. Overall Configuration	Work/Rest Cycle
Gravity Simulation	11. Data Processing
Vehicle Description	Introduction
Staging	The Data Multiplexer—Display
6. Spacecraft	Processor
Command Module	The Mission Control Computer
Mars Excursion Module	The Data Processing Computer
Earth Entry Module	The Extra Modular Data
Life Support System	Acquisition System
Heat Balance within the	The Digital Computer
Spacecraft	Magnetic Tape Storage
Micrometeoroid Shielding	Command Module
Radiation Shielding	Mars Excursion Module
Primary Power Supply	Earth Entry Module
7. Guidance, Navigation and	Mars Orbital Mapper
Stabilization	12. Logistics
Guidance	Launch Vehicles
Navigation	Launch Schedule
Main Vehicle Stabilization	13. Conclusions
System	

TABLE II

Mars Excursion Module	Aerodynamic Characteristics
Introduction	of a Blunted Cone
General Design Considerations	Ablation Calculation
Propellant Selection	Additional Shield Weight
Ascent Stage	Integration of MEM, Shield,
Flight Control Section	and Retro Package
Storage Section	Orbital Departure Retro
Propulsion Section	Package
Lander Stage	Trajectories
Living Section	Descent Trajectory
Landing Gear	Ascent Trajectory
Lander Retro Package	Guidance and Navigation
Atmospheric Entry Heat Shield	Descent
Atmosphere at Mars	Ascent
Entry Dynamics	
Selection of Vehicle	

the possibility for both inbound and outbound Venus flybys, and because it was felt that the necessary technologies could be ready by that time. Although the mission profile calls only for an outbound flyby, the return flyby is a useful alternative to reduce Earth entry velocity in the event of difficulty with Earth retro propulsion. The mission window does not fall exactly on a minimum of projected sunspot cycles, but it is near one on the downward trend, reducing the probable overall radiation dose. Shielding against possible solar flares must be provided in any event, since projected cycles cannot guarantee that no flares will occur.

The vehicle designed to undertake this mission consists of modules clustered around a central 200 foot beam (see Fig. 1). During the trip to and from Mars the entire crew lives and works in the semi-cylindrical command module (COM). The conical Mars excursion module (MEM) lands three men on the surface and later returns them to the main vehicle. The winged Earth entry module (EEM) makes the final passage into the Earth's atmosphere. The fuel for the six nuclear engines is stored in four cylindrical Earth escape fuel tanks, two spherical Mars capture fuel tanks, and two smaller spherical Mars escape fuel tanks.

Designing for the worst launch date of the twenty day window, the vehicle has an initial mass in Earth orbit of 2,783,000 pounds. Including the thirty to forty day stay on Mars, the overall mission duration is five hundred days. Six men are placed in orbit about Mars, three are landed on the surface, and all six are returned to Earth."

The students recognized readily the major importance of the decision to simulate gravity by spinup of the vehicle during most

portions of the trip as, for instance, "Cost in mass in Earth orbit due to extra structure, fuel and subsystems required to spin is approximately 250,000~~0~~" They wrestled realistically with the problems of mass distribution at various stages, of maintaining Earth communications and of navigating from a spinning vehicle, and incorporated realistic solutions in the final design. Further insight into their effort can be gained from the attached reproductions of a number of the slides used in the oral presentation. From these it is apparent that data processing and communications were certainly not slighted and the actual exploration of Mars was carefully planned and provided for in the design of the Mars Excursion Module.

Certain factors seem quite essential to the obvious success of such a systems design course. It cannot be attempted on such a scale in an astronautical area until the students have gained sufficient background in the major supporting disciplines of materials and structures, fluid mechanics and heat transfer, propulsion, system dynamics, guidance and control, communications and data processing. Interested students from other professional areas bring complementary strength in many fields such as communications and nuclear energy. These varied backgrounds must be accompanied by a sufficient maturity to be able to appreciate the interfaces between areas and to communicate fruitfully through them. There must be a willingness to search out new data in new areas and the ability to evaluate its significance. These factors are necessary to the self-confidence which is a most important ingredient.

Along with confidence, there must be interest and even enthusiasm for the project among both staff and students. The timeliness of the chosen project can do much to increase motivation.

and here there is certainly no restriction to projects in astronautics. Analagous system designs can be done in any area of engineering. Another project carried out concurrently with the Manned Mars Mission at M.I.T. was Project Transport in which the feasibility of a highspeed unconventional transportation system in the populous corridor between Boston and Washington was examined.

It is interesting to observe the intercommunication process between the student groups as they wrestle with the technical pros and cons of various approaches and realize that what is best for communications may be poor for propulsion or control and stabilization. They must learn to support their suggestions with data and analysis and yet be willing to change to meet the needs of others. Since they do not have large vested interests like many of their counterparts in industry, the students perhaps enjoy more freedom to seek novel solutions and make drastic changes rather late in the design. After years of individual study and effort they seem to relish being part of a team in which each contributes his bit to the whole and is more expert in it than anyone else. They are quite conscious that the system can only succeed if each group does its part in a responsible fashion.

The delegation of responsibility to relatively young engineers is quite characteristic of the fast-growing astronautical industry where traditional techniques often have little pertinence. Probably this knowledge is an additional stimulant to the students to indulge vigorously, creatively and cooperatively in a team effort. Such an incentive might well be lacking in more traditional areas of engineering in which the young graduate is expected to put in numerous years of apprenticeship. It

might also be lacking in a society which reveres tradition and age more than the American society. This would seem to have particular pertinence in those older cultures such as the Indian in which industry is just coming into prominence. Yet the need for engineers in such cultures so far outstrips the supply as to accentuate the conflict between old and new. In preparing students for participation in the basic industries such as steel and electric power and nuclear power, the systems design approach with a team effort may be very profitable because the scale of such engineering requires cooperative interplay between specialist groups whatever the society.

Perhaps the easy informality in the relationship between the American student and his teachers is a major reason for the success of a systems design course. Direct interchange of ideas is not so hampered by feelings and traditions of rank and position as in many other societies. The professor and the expert from industry are actually quite accessible to the student who is comparatively skilled in communicating with such people. The psychological barriers are not so high.

For both the student and the faculty member the systems design course is in many ways analagous to a thesis-type of effort. However, the one-to-one relation between student and teacher characteristic of the thesis is here expanded to a group-to-group relationship. Of course such a relationship requires organization, communications and a common agreed focus on an integrated design. It is not pure research. Rather it contains in reasonable proportions many of the ingredients essential to the successful engineering of modern systems.

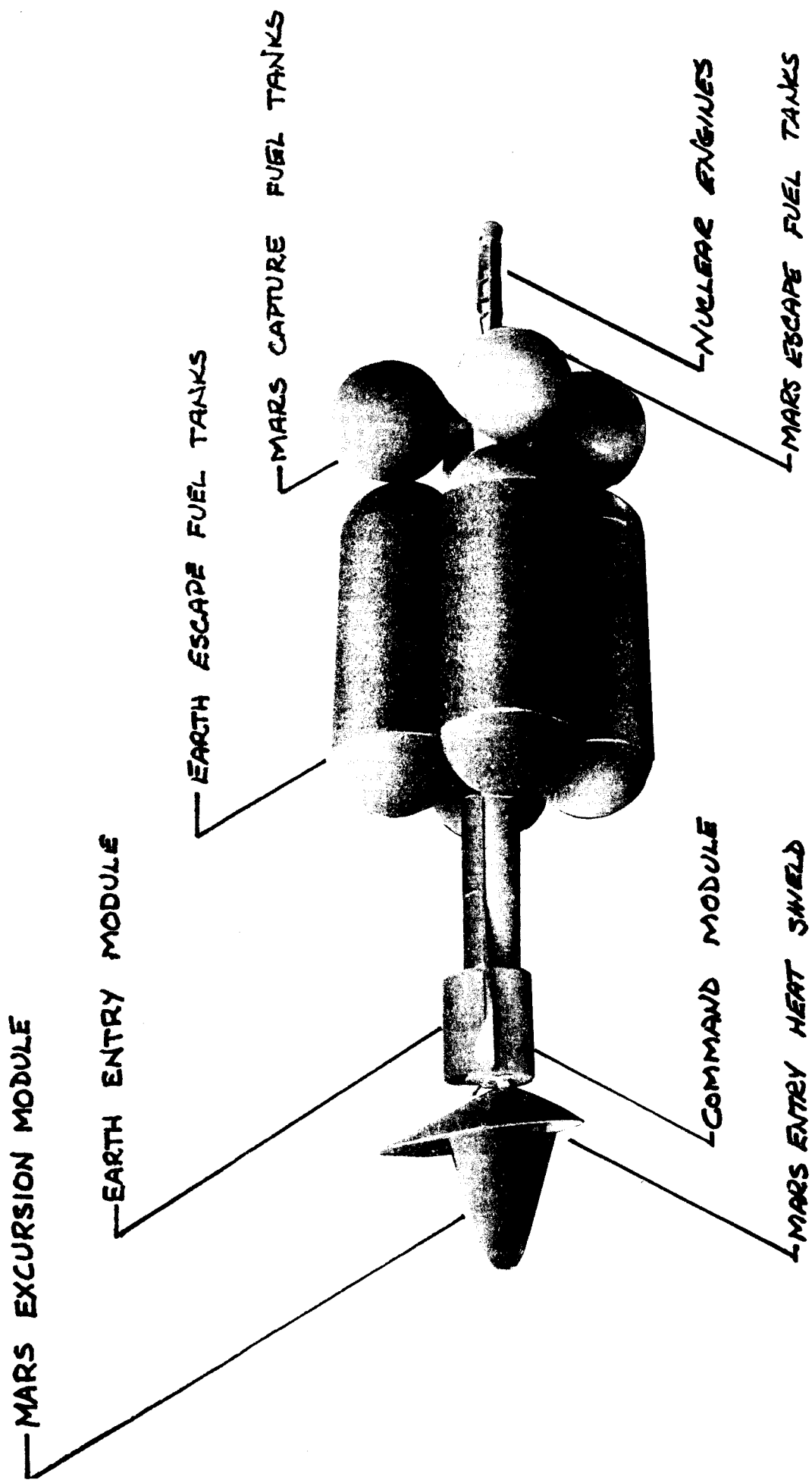


FIG. 1 - MAIN VEHICLE

# MARS EXCURSION MODULE

